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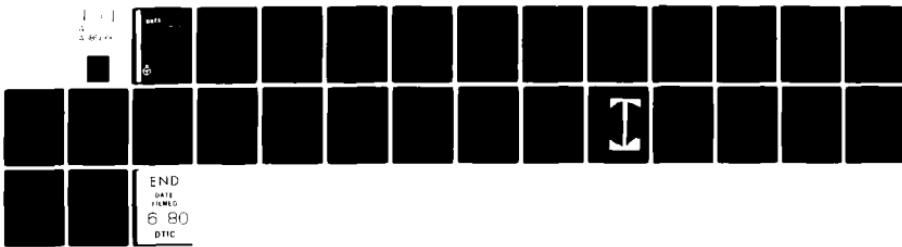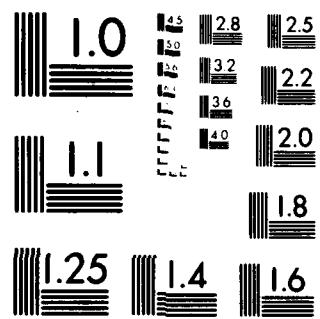
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by

C.L. Chenier and G.A. Hill

PCN 13E01

May 1980

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ABSTRACT

The swelling and shrinking of Newtonian jets issuing from
circular orifices or slits has been examined. Equations predicting die
swell ratio and downstream flow characteristics are developed. The
scatter of experimental data has been studied and the factors contributing
to this phenomenon are presented. The die swell ratios and jet shapes
versus Reynolds numbers for Newtonian liquids are empirically shown.

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INTRODUCTION

The physical characteristics of liquids can greatly affect
the performance of mechanical devices used to transport, store or dis-
seminate them. For example, many liquids when thickened by polymers
undergo not only viscosity changes which greatly affect their flow
properties but also become viscoelastic in nature which can have con-
siderable effect on their transient flow properties.

One method which has considerable use in the measurement of
'elasticity' involves simply pushing the liquid in question out of the
end of a small diameter tube. For some non-Newtonian liquids it was ob-
served a long time ago (1) that this could result in jets with diameters
considerably larger than the original diameter of the tube or slit.
Although this phenomenon has been given several names, the term most
commonly used is "die swell". Die swell was considered for over half a

century to be due solely to the elastic properties of non-Newtonian liquids. However, in 1961, Middleman and Gavis (2) observed the same phenomenon for Newtonian liquids. They found that for flows below Reynolds number 16 the jets expanded in diameter, whereas at higher Reynolds numbers they contracted. This expansion and contraction was somewhat less than that observed for most viscoelastic liquids but was still significant and was unaccounted for in any theory at that time. In the same report, they attempted to account for this phenomenon by an overall mass and momentum balance between the tube exit and an arbitrary distance downstream where it was assumed the velocity profile was flat and the pressure was atmospheric. Their analysis showed that the swelling effect was due to the relaxing axial velocity profile at the tube exit and to surface tension, although Gavis (3) later pointed out an error in this analysis which showed surface tension did not contribute to the swelling phenomenon.

THEORY

Since the initial discovery of die swell for Newtonian liquids there have been several more theoretical interpretations of this phenomenon. Richardson (4) performed an overall momentum balance but failed to include any terms other than the velocity integrals in his expression for the die swell ratio. Only recently has the die swell phenomenon been accurately predicted using numerical techniques (5,6). In these analyses, the inclusion of the singularity boundary condition at the die exit seems to preclude any hope of a successful analytical solution.

The overall mass and momentum balance on a jet issuing from a slit or tube provides much useful information on the die swell phenomenon. Consider the jet depicted in Figure 1. If we assume a flat velocity profile downstream and atmospheric pressure across the jet, the mass balance between position 0 and position 1 gives (Cartesian coordinates):

$$2\rho \int_0^{Y_0} u\,dy = 2\rho U_\infty Y_\infty \quad\ldots\ldots\ldots\ldots (1)$$

... and the momentum balance gives:

$$\rho \int_0^{Y_0} u^2 dy + \int_0^{Y_0} p \, dy + \int_0^{Y_0} \tau_{xx} dy = \rho U_\infty^2 Y_\infty \quad \ldots \ldots \ldots \ldots \quad (2)$$

... where it has been assumed that gravitational and surface tension
forces are negligible. Some algebraic manipulation of these two com-
plete equations gives a more complete equation for the die swell ratio
than given by Richardson (4):

$$\chi = Y_\infty/Y_0 = \frac{\rho\{\int_0^1 u \, dy\}^2}{\rho \int_0^1 u^2 dy + \int_0^1 p \, dy + \int_0^1 \tau_{xx} dy} \quad \ldots \ldots \quad (3)$$

... where the integrals have all been normalized by Y_0. The above equation
implies that the final die swell ratio is determined completely by the
conditions at the end of the slit provided the assumptions of negligible
gravity and surface tension effects are correct. If the last two terms
of the denominator of Equation 3 are negligible, then clearly the largest
value that the die swell ratio could have would be 1.0. Thus, unless
these terms provide a net negative value to the denominator there can be
no swelling. With all the above assumptions and further assuming that the
velocity profile remains parabolic right up to the slit exit, the velocity
integrals in Equation 3 yield a value of 0.833 for the die swell ratio
from a slit. Similarly, the die swell ratio for flow from a tube can be
calculated as 0.866. These limiting conditions are approached at high
Reynolds number flows (2) where numerical simulations have predicted the
velocity profiles at the slit exit remain very nearly parabolic (6).

The fact that the velocity profile is affected by the Reynolds
number has been demonstrated experimentally. Goulden and MacSporran (7)
used a laser anemometer to measure velocity profiles in viscoelastic
liquids over a range of Reynolds numbers. At higher Reynolds numbers, their
plots demonstrated that longer distances downstream are required before
the axial velocity profiles become flat. The reason for this phenomenon

can be understood from an analysis of the axial momentum equation (x-direction) at steady state:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial \phi}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial x^2}\right) \quad \ldots\ldots\ldots (4)$$

This equation is non-dimensionalized using the technique of Bird et al. (8) which requires multiplication by a distance term and division by a velocity term. This combination is arbitrarily chosen to be $2Y_0/U_0^2$ and the dimensionless parameters are:

$$x' = x/2Y_0, \quad y' = y/2Y_0, \quad u' = u/U_0$$
$$v' = v/U_0, \quad \phi' = \phi/U_0^2, \quad Re = 2Y_0 U_0/\nu \qquad \ldots\ldots\ldots (5)$$

Substituting 5 into 4 gives:

$$u'\frac{\partial u'}{\partial x'} + v'\frac{\partial u'}{\partial y'} = -\frac{\partial \phi'}{\partial x'} + \frac{1}{Re}\left(\frac{\partial^2 u'}{\partial x'^2} + \frac{\partial^2 u'}{\partial y'^2}\right) \quad \ldots\ldots\ldots (6)$$

The individual terms in Equation 6 are now analyzed for the die swell problem making appropriate assumptions. For die swell, the flow remains almost parabolic right up to the tube exit for Reynolds numbers greater than about 10, as has been shown by numerous experimental and theoretical evaluations (4,5,6,7). At the slit exit, although the velocity does begin to relax, it is highly probable that the transverse velocity differentials are much greater than the axial ones, so that:

$$\frac{\partial^2 u'}{\partial y'^2} = -0.75 \gg \frac{\partial^2 u'}{\partial x'^2} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

... for a parabolic velocity profile at the exit. The pressure gradient for laminar flow in a slit is:

$$\frac{\partial \phi}{\partial x} = -\frac{3\nu U_0}{Y_0^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

... or in dimensionless form:

$$\frac{\partial \phi'}{\partial x'} = -\frac{12}{Re} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

It is not obvious that the pressure gradient at the die swell exit is the same as it is upstream; however, it is intuitively obvious that it will be much less at the exit and probably is some small fraction, f, of what it is upstream:

$$\left.\frac{\partial \phi'}{\partial x'}\right|_{exit} = f\left.\frac{\partial \phi'}{\partial x'}\right|_{upstream} = f\frac{-12}{Re} \quad \ldots\ldots\ldots\ldots \quad (10)$$

With these assumptions, the terms on the right hand side of Equation 4 are inversely proportional to the Reynolds number:

$$RHS = \frac{12f}{Re} - \frac{3}{4Re} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

Thus the terms on the left hand side of Equation 4 must also be inversely proportional to the Reynolds number. If the profile remains parabolic, then only the partial derivative $\partial u'/\partial x'$ can vary. Thus $\partial u'/\partial x'$ must be inversely proportional to the Reynolds number, and for high Reynolds number flows $\partial u'/\partial x'$ will be small and high values of x' (long distances downstream) will be required to achieve a flat profile. Similarly, at low Reynolds numbers $\partial u'/\partial x'$ will be high and smaller distances downstream will be required to achieve a flat profile.

It must be pointed out that this analysis used assumptions which appear to be upheld by experimental and theoretical evidence. At very low Reynolds numbers, however, the velocity profile may vary significantly from parabolic and this analysis should not be expected to hold.

EXPERIMENTAL

Die swell experiments were conducted to complement and extend the available published data. The experiments were conducted at room temperature with the apparatus depicted in Figure 2. A large tank was pressurized sufficiently to force the liquid through the tube at the

desired flow rate (calculated by the Hagen-Poiseuille equation). This
tank was then disconnected from the pressure source to eliminate spurious
pressure fluctuations. The liquid to be pumped was maintained in a 0.15
litre or 4.5 litre stainless steel reservoir depending on the volume of
liquid required. The flow rate was regulated with a micrometer needle
valve and monitored with a rotameter. The rotameter served only to
ensure that a constant flow rate was being maintained. The actual flow
rate was determined for each experiment by collecting an arbitrary mass
of liquid over a measured time interval. This was the simplest procedure
due to the impracticality of calibrating every rotameter for every liquid.
The liquid jets issuing from the tubes were photographed with a 35 mm
camera using either a microscope for very small jets or a camera bellows
for larger jets. The light source was located behind the jet, resulting
in photographs similar to that shown in Figure 3. Glass rods of known
diameter were also photographed in this manner to ensure that no errors
in diameter measurements were resulting from unknown optical effects.
The diameters of the jets and glass rods were calculated with reference
to the known outside diameters of the hypodermic tubes. The glass rod
experiments demonstrated that the technique was accurate to within 0.5%
of the true diameter. The diameter measurements were made from enlarged
glossy prints using a calibrated magnifier lens.

The Newtonian liquids used in these experiments consisted of
mixtures of glycerol and water. The concentrations, densities (measured
with pycnometers), and viscosities (Canon-Fenske) are listed in Table 1.
The room temperatures at which the die swell experiments and physical
measurements were made are also listed in Table 1.

The tubes used in these experiments were stainless steel hypo-
dermic needles. Their ends were carefully ground using a carborundum
stone and fine grade crocus cloth. The inside edges of the orifices were
smoothed and deburred with stilettos. Ten different tubes were used in
these experiments and their characteristics are listed in Table 2. Dia-
meters were measured under a microscope in three different cross-
sections to ensure circularity as listed in Table 2. The ends of the

tubes were tapered from their outside diameters to their inside diameters (as shown in Figs. 2 and 3) in order to reduce the tendency of the liquid to spread along the orifice edge. The lengths of the tubes were several factors larger than their diameters as listed in Table 2. This reduced the effect of entrance phenomena on the die swell measurements (9).

RESULTS AND DISCUSSION

The experimental data for the die swell ratio are listed in Table 3 as a function of Reynolds number and plotted in Figure 4 (triangles). The solid lines on this graph represent an envelope of the original data gathered by Middleman and Gavis (2). The circles indicate the data of Goren and Wronski (10) and the crosses indicate the extremes of the data gathered by Gavis and Modan (9). The data gathered by all investigators show considerable amounts of scatter.

The causes for this experimental scatter are a combination of many factors some of which are listed below.

(i) The actual measurement process off the photographs can yield results which vary from investigator to investigator. In one study here, it was found that two separate investigators using two different measuring devices (a graduated magnifier and a steel machinist's scale) produced data that was generally within a range of ± 1.0% of the actual percentage die swell, but differences as high as ± 3.0% were observed. This could account for much of the scatter of our own data and probably contributes to the scatter of others.

(ii) Gavis and Modan (9) found that the length to diameter ratio of the tube affected the jet shrinkage at Reynolds numbers greater than 16 but they could not find any correlation at lower Reynolds numbers. We avoided this phenomenon to a large extent by employing tubes with length to diameter ratios 9 or greater.

(iii) Although the original investigators (2) indicated that surface tension contributed to die swell, Gavis (3) showed theoretically that this was incorrect and Goren and Wronski (10) could not find any experimental proof of this phenomenon. Reddy and Tanner's numerical prediction (5) also indicated that surface tension had little effect at the Reynolds numbers studied here.

(iv) Goren and Wronski (10) speculated that viscous heating in the capillary could result in distorted velocity profiles and incorrect die swell ratios. This effect would also tend to decrease the liquid viscosity and increase the Reynolds number.

(v) Goren and Wronski (10) also speculated that air friction on the jet could be considerable at higher Reynolds numbers and this could increase the die swell ratios considerably.

(vi) Most investigators have tried to avoid the effects of gravity on their experiments by either shooting their jets horizontally and considering only the shapes before the jets began to curve downwards or by shooting their jets into a non-soluble liquid of similar density. However, Hill (6) has numerically predicted that for small diameter tubes, as used in most experimental work, gravity has negligible effect in the axial direction.

To test the effect of tube diameter on the die swell ratio a series of experiments were conducted using tubes of various diameters and liquids of various viscosities. All runs were made at Reynolds number 7.0 and the data are listed at the top of Table 3. The results of these tests are plotted in Figure 5. This graph demonstrates that there is no consistent effect of tube diameter on the die swell ratio. Also, because of the random location of the various viscosity liquids for each tube, it was concluded that viscous heating was not a factor contributing to scatter at this flow rate. Rather, the measured die swell ratios appear to be affected by some individual characteristics of each tube. This is noticeable by the fact that some tubes yielded consistently higher ratios than other tubes. One tube resulted in swelling of 12% to 19% whereas most of the data varied from 7% to 10%. Upon close microscopic

examination of this tube, it was discovered that a slight taper existed
around the inside circumference. This resulted in an expansion affect
on the liquid before it even reached the end of the tube. Calculations
showed this taper resulted in an exit diameter 9% greater than the tube
diameter and this accounts for the unusually large die swell ratios
measured from this tube. None of the data gathered from this tube was
used in Figure 4. Allan (11) has numerically predicted the effects of
tapers on the die swell ratio for creeping flow and our experimental
results would seem to confirm his prediction. The shape of the orifice
is therefore very critical to experimental measurements of die swell
and undoubtedly plays a big role in the scatter of experimental data.
Six various possible configurations of the orifice shape are shown
schematically in Figure 6. As most experimental measurements of die
swell are performed on small diameter tubes, the difficulty of achieving
the perfect orifice is significant.

Several photographs were examined for jet shapes; the data
are listed in Table 4 and depicted in Figure 7. Here again, the large
error due to the above mentioned experimental difficulties must be kept
in mind. The fact that the low Reynolds number jet shapes do not leave
from the tube corner could be due either to slightly tapered orifices
or to spreading of the liquid along the orifice edge. In either case,
the experimental data still compare favorably to the data of Goren and
Wronski (10), who based their calculations on the initial jet diameter
and not the tube diameter. The jet shape data also illustrated the fact
that high Reynolds numbers required longer downstream distances before
flat surface profiles are achieved, as predicted in the theory. At low
Reynolds numbers, when $X_0 \approx Y_0$, the jet shape does not keep contracting,
however, probably due to the non-parabolic velocity profile at the tube
exit.

CONCLUSIONS

The overall mass and momentum balances yield an equation for
the die swell ratio which shows that swelling at the tube exit is caused

by a net negative pressure and axial stresses across the tube. The rela-
xation of axial velocity and surface shape can be shown to be a function
of the Reynolds number. At high Reynolds numbers long distances are
required downstream before these parameters become completely relaxed.

The experimental measurements of die swell show a large degree
of scatter in the data for all investigations. This scatter has been
demonstrated to be due primarily to the accuracy of the measurement
technique and to the quality of the tube orifices. Due to the importance
and ease of this technique for measuring elasticity in non-Newtonian
liquids, it would seem profitable to invest time in the design and con-
struction of devices to overcome these present handicaps.

The experimentally measured jet shape data plus the relaxing
axial velocity profiles measured by Goulden and MacSporran (7) have
demonstrated the correctness of the dimensional analysis which predicts
larger downstream distances are required to overcome disturbances at
higher Reynolds numbers.

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NOMENCLATURE

p = pressure

u = axial velocity

U_0 = average bulk velocity far upstream

U_M = maximum axial velocity

U_∞ = axial velocity far downstream

v = transverse velocity

V_M = maximum transverse velocity

x = axial position

X_0 = characteristic length downstream

y = transverse position

Y_0 = characteristic length or width across jet

Y_∞ = jet width far downstream

Greek Symbols

ν = kinematic viscosity

ρ = density

τ_{xx} = axial stress

ϕ = pressure variable

χ = die swell ratio

TABLE 1

NEWTONIAN FLUIDS USED

Liquid No.	% Glycerol by Volume	Density (g cm^{-3})	Viscosity (cm^2 s^{-1})	Temperature (°C)
1	0	0.997[+]	0.01	25
2	85.1	1.221	0.79	24
3	87.8	1.231	1.28	25
4	90.5	1.238	1.78	25
5	91.3	1.243	2.39	23
6	91.3	1.242	2.40	23
7	93.8	1.245	2.81	25
8	94.6	1.248	3.84	25

[+] CRC Handbook

TABLE 2

TUBES USED IN DIE SWELL EXPERIMENTS

Tube No.	Outside Diameter (cm ± 0.0005)	Inside Diameter (cm ± 0.0005)		L/D Ratio
1	0.040	0.024	0.023	13
2	0.072	0.043	0.044	15
3	0.090	0.058	0.057	0.058	18
4	0.090	0.058	0.058	16
5	0.089	0.060	0.060	0.059	45
6	0.125	0.085	0.084	0.083	9
7	0.124	0.085	0.084	0.083	36
8	0.165	0.116	0.116	0.113	17
9	0.183	0.132	0.132	0.117	20
10	0.240	0.181	0.176	0.176	18

TABLE 3

EXPERIMENTAL DIE SWELL DATA

Liquid No.	Tube No.	Reynolds No.	Die Swell x
3	1	7.1	1.07
3,4	2	7.2 - 7.3	1.12 - 1.19
4,7	3	6.9 - 7.4	1.07 - 1.08
4,7	6	6.6 - 7.2	1.09 - 1.11
7,8	8	6.8 - 7.4	1.05 - 1.07
7,8	9	6.7 - 7.2	1.06 - 1.08
8	10	6.3 - 6.9	1.08 - 1.10
5	5	2.27	1.137
5	4	4.00	1.097
5	7	5.26	1.136
5	6	10.65	1.011
2	7	15.4	1.035
2	8	22.1	0.970
2	4	47.0	0.933
3	8	17.9	0.981
3	8	24.0	0.959
3	8	14.8	0.994
3	8	18.1	0.981
2	6	62.5	0.907
2	7	33.8	0.965
2	8	42.6	0.936
2	8	89.9	0.896

TABLE 4

EXPERIMENTAL JET SHAPE DATA
(DIE SWELL RATIOS)

| Distance Downstream x/Y_o	Reynolds Number							
	4.0	7.1	14.8	18.1	24.0	47.0	62.5	89.9
0.00	1.019	1.008	1.016	1.015	1.015	1.011	1.003	0.998
0.40	1.052	1.019	1.000	0.992	0.981	0.978	0.955	0.947
0.80	1.075	1.042	0.994	0.981	0.970	0.956	0.939	0.930
1.20	1.086	1.053	0.994	0.981	0.959	0.944	0.923	0.919
1.60	1.097	1.059	0.994	0.981	0.959	0.939	0.915	0.911
2.00	1.097	1.064			0.959	0.933	0.913	0.908
2.40		1.064				0.933	0.907	0.905
2.80							0.907	0.899
3.00							0.907	0.896
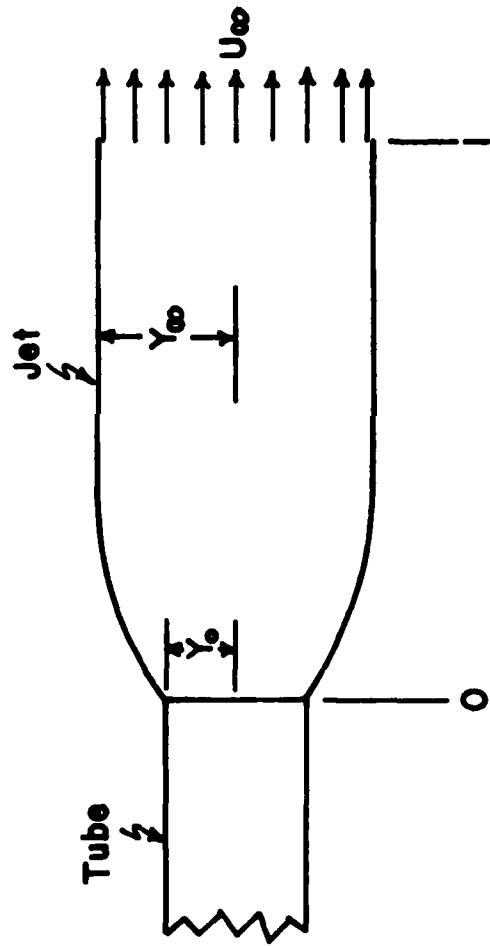
Figure 1.   Schematic of a Swelling Jet
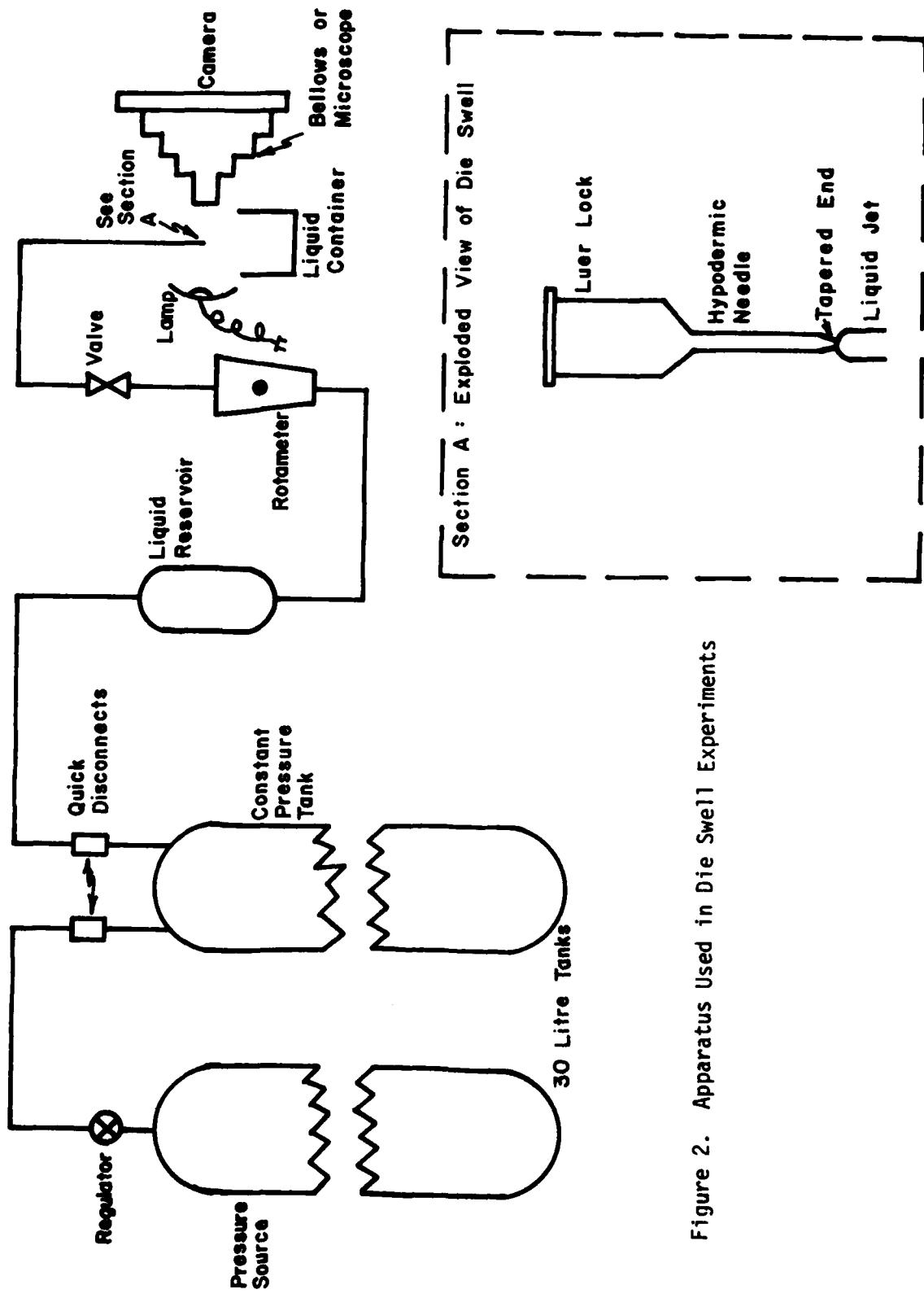
Figure 2. Apparatus Used in Die Swell Experiments
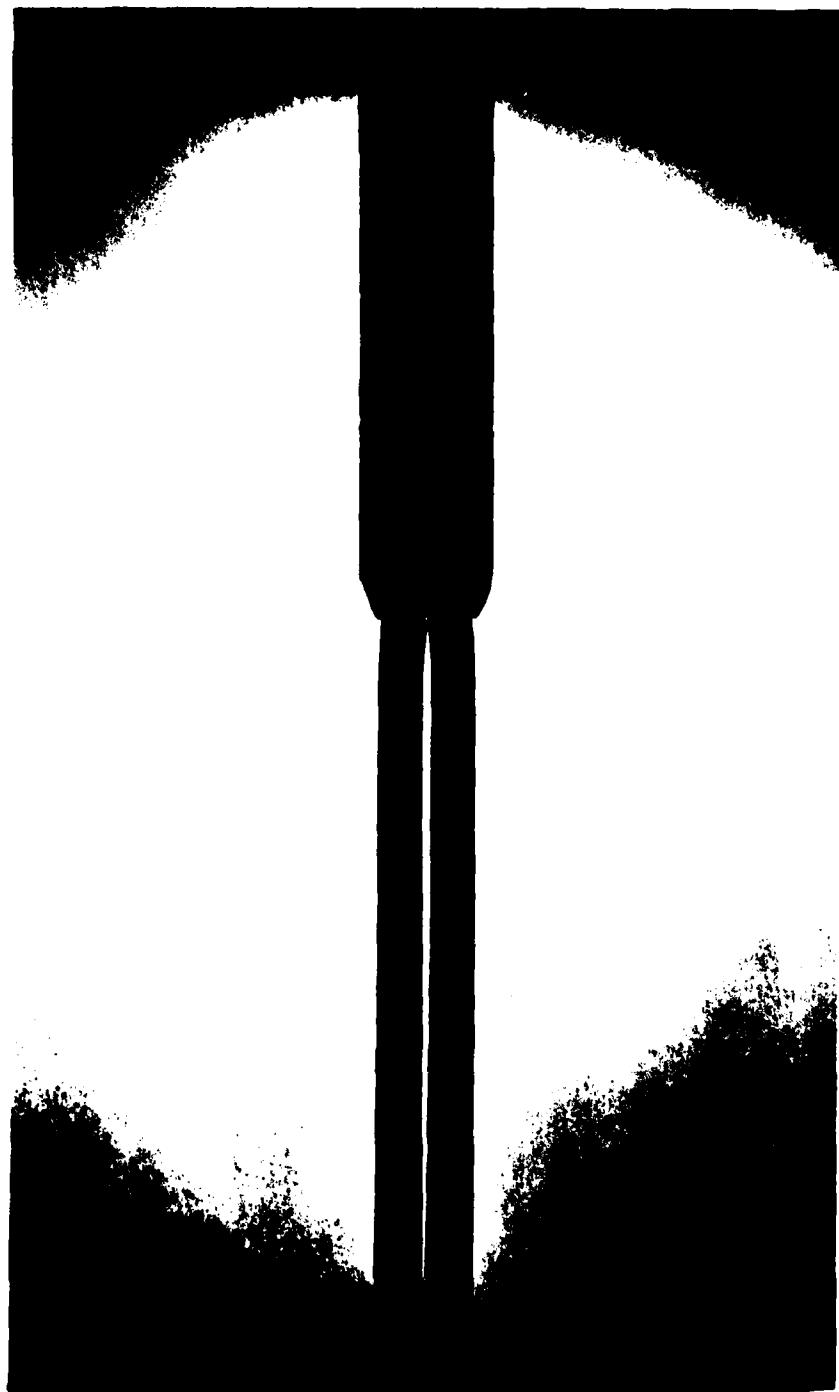
Figure 3.   A Typical Die Swell Jet
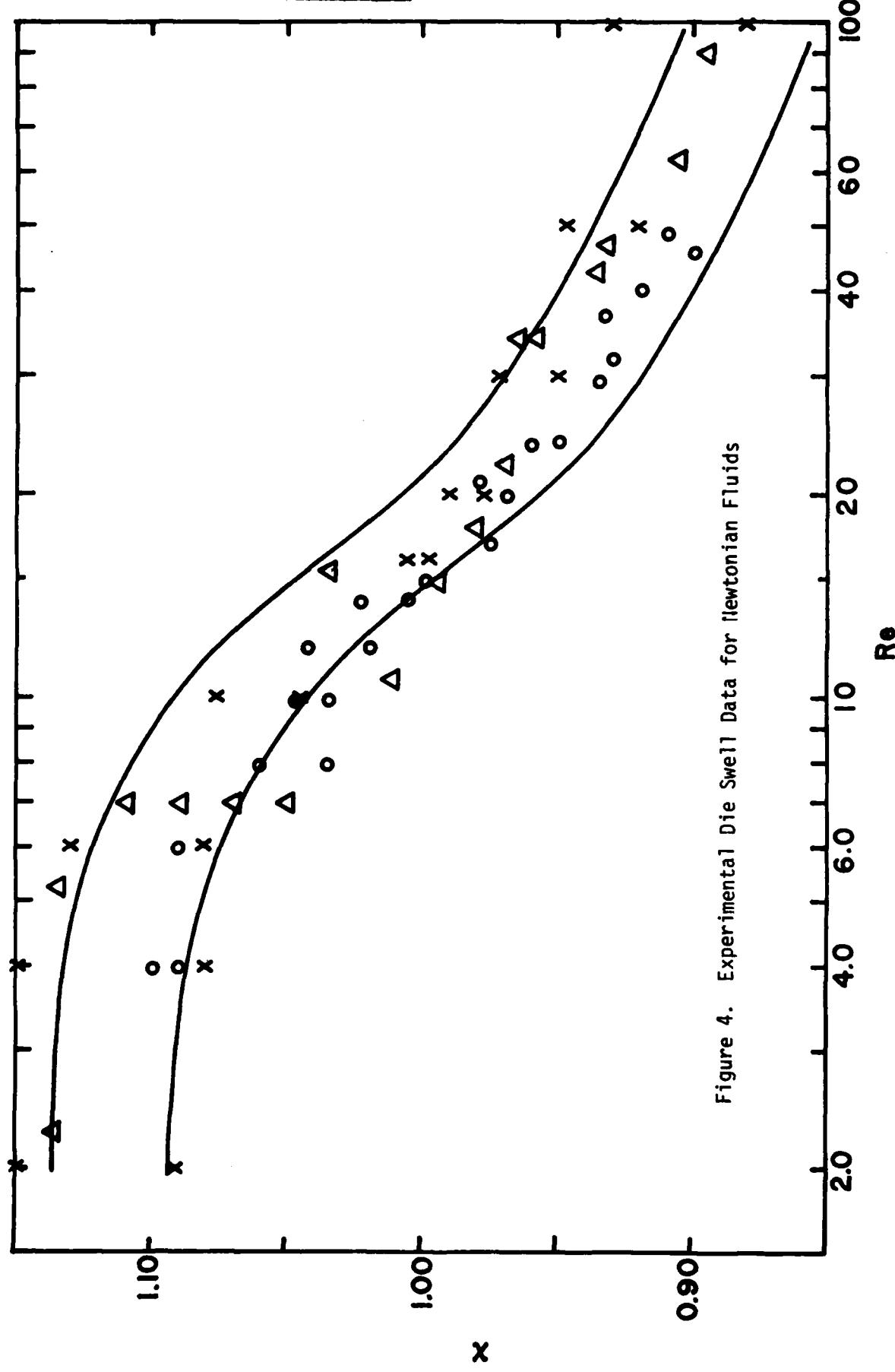
Figure 4. Experimental Die Swell Data for Newtonian Fluids

Figure 5. Experimental Values of Die Swell Ratio for Different Liquids and Tubes at Reynolds Number 7.0

Key

- ○ ν = 1.28 cm^2 s^{-1}
- ● ν = 1.78 cm^2 s^{-1}
- △ ν = 2.81 cm^2 s^{-1}
- ▲ ν = 3.84 cm^2 s^{-1}

Tube Diameter (mm)
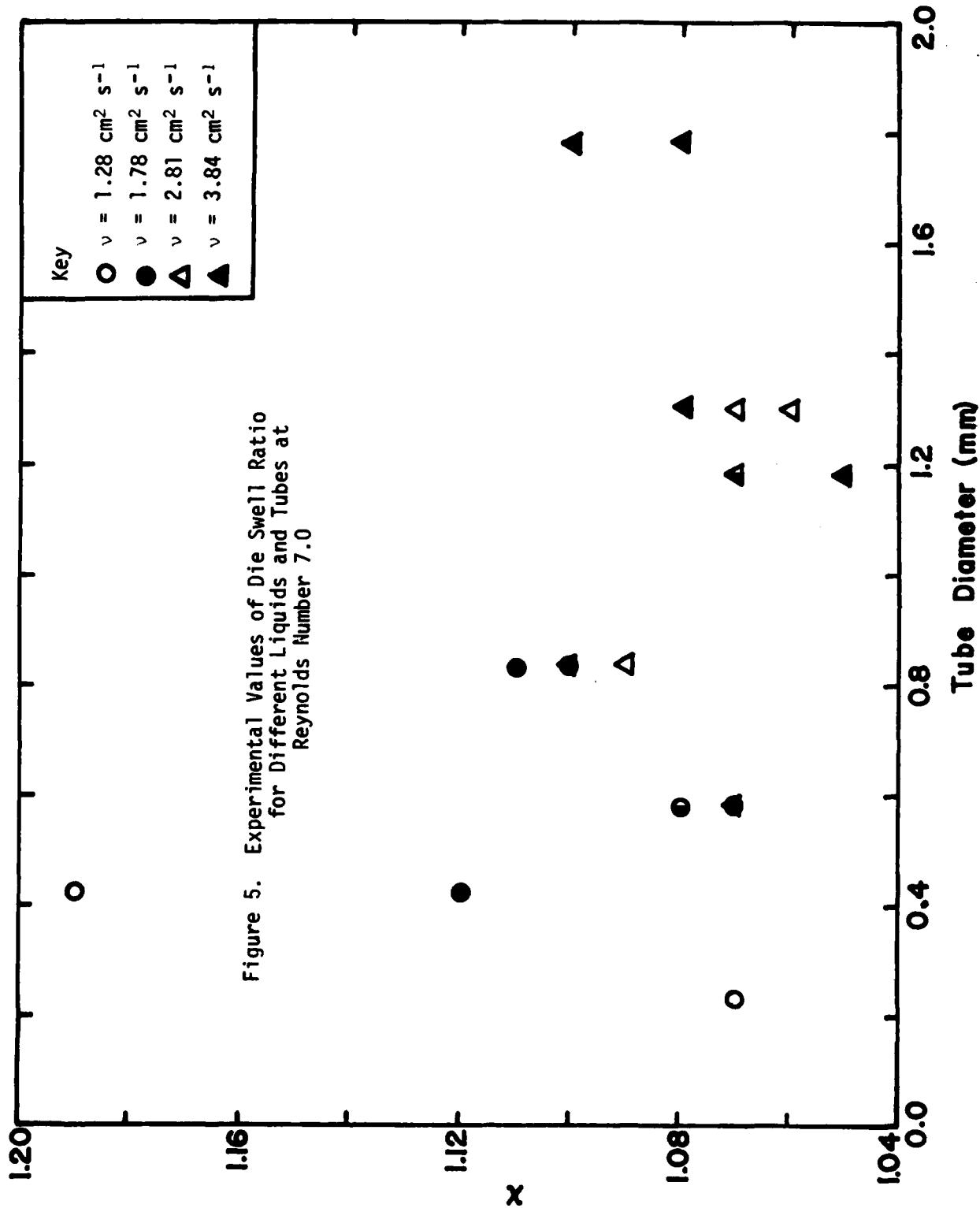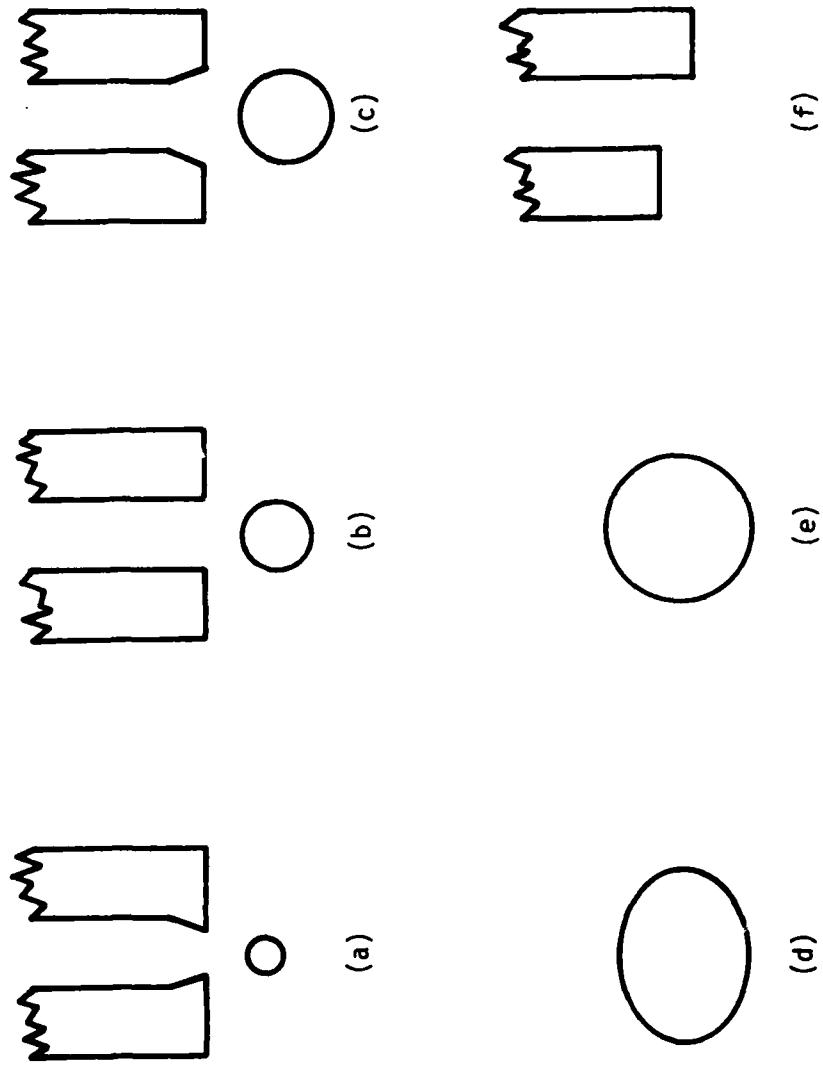
Figure 6. Various Orifice Configurations: (a) tapered in ... die swells too small, (b) straight ... die swells correct, (c) tapered out ... die swells too large, (d) elliptical ... incorrect die swells, (e) circular ... correct die swells, (f) not square ... incorrect die swells
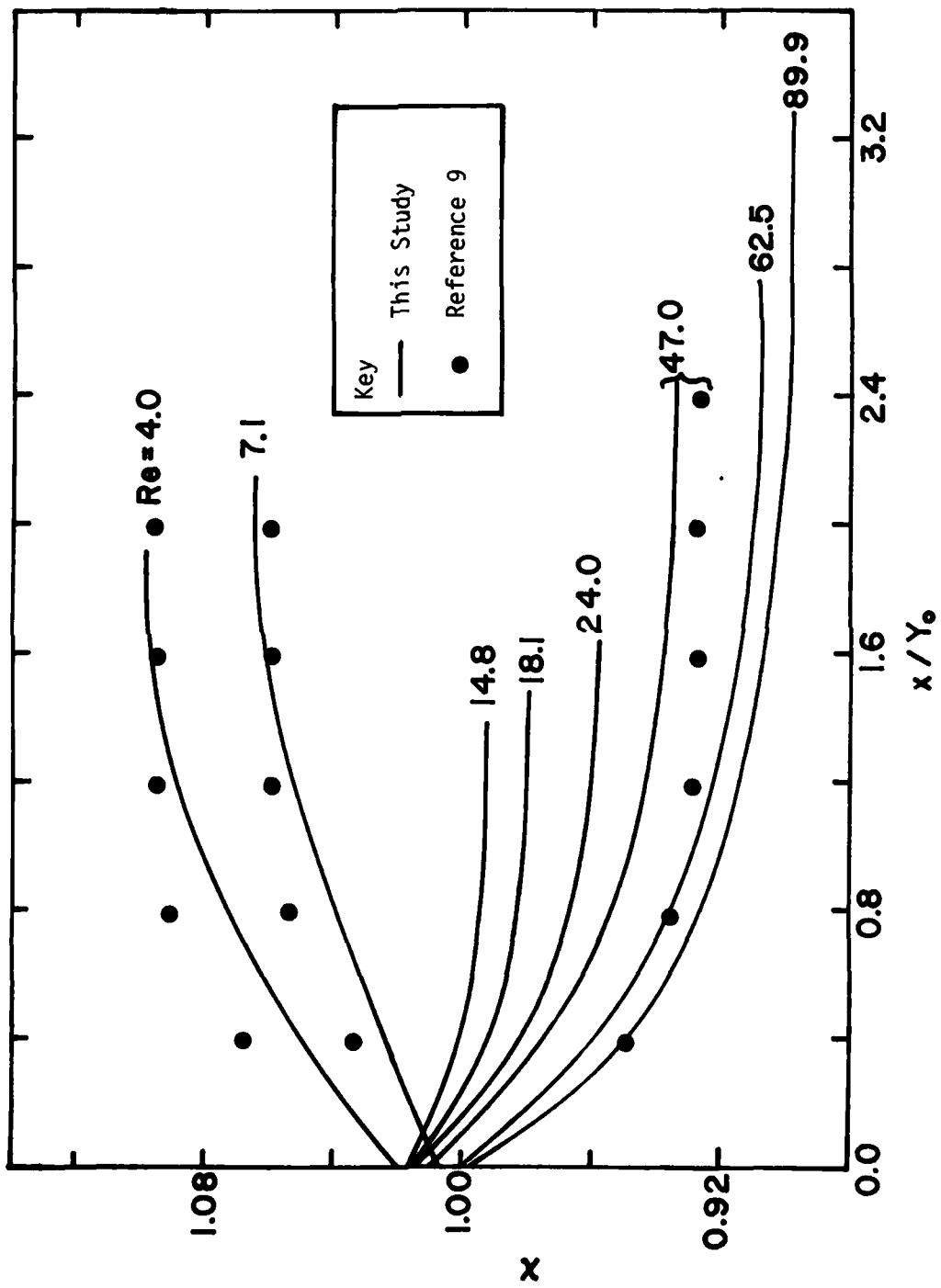
Figure 7. Experimental Jet Shapes

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